

Chemical Abundances of Bright Giants in the Mildly Metal-Poor Globular Cluster M4

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Abstract:

We present a chemical composition analysis of three dozen giant stars in the nearby “CN-bimodal” mildly metal-poor ($<[\text{Fe}/\text{H}]> = -1.18$) globular cluster M4. The analysis combined traditional spectroscopic abundance methods with modifications to the line-depth ratio technique pioneered by Gray (1994). Silicon and aluminum are found to be primordially overabundant by factors exceeding the mild overabundances usually seen in α - and light odd elements among halo field and globular cluster giants of comparable metallicity. In addition, barium is found to be overabundant by a factor of about four. Superimposed on the primordial abundance distribution in M4, there is evidence for the existence of proton-capture synthesis of C, O, Ne, and Mg.

1 Introduction

As isolated laboratories of stellar evolution, individual globular clusters were once considered to be simple systems, having formed coevally, out of the same material, and exhibiting cluster-to-cluster differences due to only metallicity and age effects. In reality, clusters of similar age and metallicity exhibit differences in their colour-magnitude diagrams and many of the elemental abundance patterns deviate from the predictions of stellar evolution theory. Many low-metallicity globular clusters exhibit large star-to-star variations of C, N, O, Na, Mg, and Al abundances. These elements are those that are sensitive to proton-capture nucleosynthesis.

In clusters where giant star samples have been sufficiently large, the abundances of O and Na are anticorrelated, as are those of O and Al (as well as sometimes Mg and Al). Previous clusters studied by the Lick-Texas group (including M3, M5, M10, M13, M15, M71, M92, and NGC7006) span a range in metallicities, from $-0.8 \leq [\text{Fe}/\text{H}] \leq -2.24$. In the higher-metallicity clusters, the abundance swings are muted. In all of the clusters, the abundance swings are observed to be a function of giant branch position. This relationship is consistent with material having undergone proton-capture nucleosynthesis (via the CN-, ON-, NeNa-, and/or MgAl-cycles) and brought to the surface by a deep-mixing mechanism. Deep mixing, according to theory (Sweigart & Mengel 1979) should become less efficient and possibly cut-off as metallicity increases. The metallicity of M4 places it among clusters in which the O versus Na and Mg versus Al anticorrelations might be expected to be largely diminished.

There are also some clusters (including M5, NGC3201, NGC6752, 47 Tuc, and ω Cen) for which distinctly bimodal distributions of cyanogen strengths at nearly all giant branch positions

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have been uncovered. These clusters apparently have had different nucleosynthesis histories. Among these CN-bimodal clusters is M4 (Norris 1981; Smith & Norris 1993), the nearest, brightest, and one of the most accessible targets to study the CN-bimodal phenomena. For the purposes of this colloquium, only certain aspects of our M4 work will be highlighted. Details of the full analysis are presented in Ivans *et al* (1999).

2 Getting the Red Out

While M4 may be the closest globular cluster, it also suffers from interstellar extinction that is large and variable across the cluster face. The line-of-sight to the cluster passes through the outer parts of the Scorpius-Ophiuchus dark cloud complex. A reddening gradient exists across the face of the cluster (Cudworth & Rees 1990; Liu & Janes 1990; Minniti *et al* 1992). And, the dust extinction probably varies on small spatial scales as well. This is suggested by the colour-magnitude diagram of M4, where the subgiant and giant branches are broader than expected, given the errors in the photometry (see figure 1) as well as by observations of the $\lambda 7699\text{\AA}$ K I interstellar line towards individual M4 stars (Lyons *et al* 1995). Figure 1 also shows that the reddening cannot reliably be estimated for individual M4 stars to the level needed to map broad-band photometric indices onto stellar parameters. Instead, another reliable temperature estimation method is required.

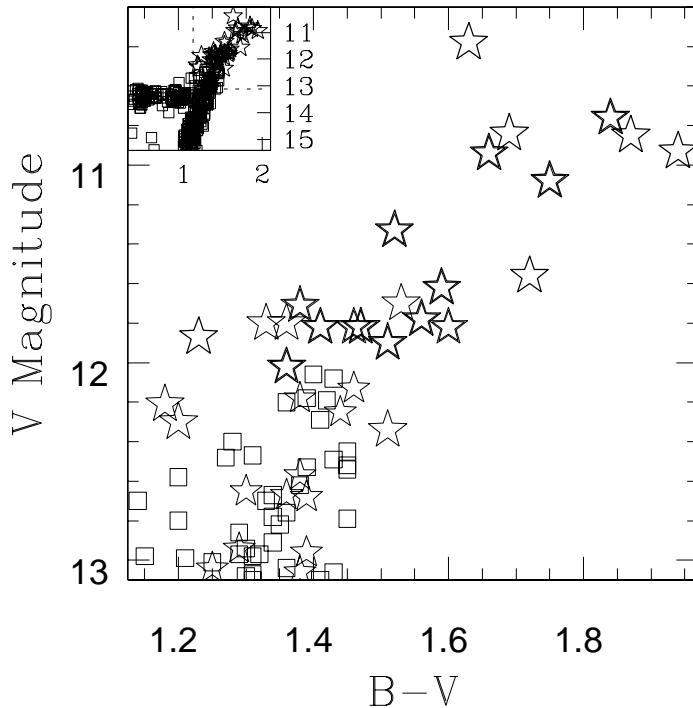


Figure 1: A colour-magnitude diagram of M4, with photometry from Cudworth & Rees (1990), showing the positions of our program stars (\star) on the giant branch. The inset diagram shows the program stars plotted in relation to all Cudworth & Rees M4 stars of magnitude ≤ 15.5 (adapted from Fig. 1 in Ivans *et al* 1999).

We combined traditional spectroscopic abundance methods with modifications to the line-depth ratio technique pioneered by Gray (1994) to determine the atmospheric parameters of our stars. The “Gray” method relies on ratios of the measured central depths of lines having very different functional dependences on photometric indices and/or Teff to derive accurate relative

temperature rankings (eg. vanadium versus neutral or ionized iron). Gray's work was done on Pop. I main sequence stars and has since been expanded by Hiltgen (1996) for applications to subgiants of a range of disk metallicities. Happily, many of Gray's line depth ratios are also sensitive Teff indicators for lower metallicity very cool RGB stars. The line depth ratios vary more than one dex in spectra of giants of moderately metal-poor clusters, and thus can indicate very small Teff changes. However, these relationships begin to approach unity among the coolest stars. While a tremendously useful tool, the "Gray" method cannot be applied to all stars of all clusters: these ratios probably will be less useful as temperature indicators for the coolest stars of appreciably more metal-rich globular clusters (where the lower temperatures and higher metallicities conspire to saturate and blend virtually all of the "Gray" spectral features). However, the method was successfully employed in our work on M4 and is currently being applied to other clusters in the process of analysis.

Our initial Teff calibration of the M4 line depth ratios was set through a similar analysis of RGB stars of M5 (a cluster of very similar metallicity to M4 but suffers little from interstellar dust extinction). We discuss the details of the correlations and transformations in Ivans *et al* (1999). While we used the line-ratio method to rank the stars, final temperatures were determined from full spectral analyses. Our results for individual stellar parameters compare well with M4 stars in the literature. Taking advantage of the non-photometric means by which we obtained our temperatures, we then derived an average $E(B - V)$ reddening of 0.33 ± 0.01 (which is significantly lower than that estimated by using the dust maps made by Schlegel *et al* 1998 but is in good agreement with the M4 RR Lyrae studies by Caputo *et al* 1985). Finally, as a confirmation of the method, we derived individual stellar extinctions that not only correlate extremely well with IRAS 100 micron fluxes but also with $E(B - V)$ estimates derived independently in interstellar absorption studies of potassium by Lyons *et al* (1995).

3 Abundance Results

We performed line-by-line abundance analyses to determine the final model atmosphere specifications. Our final models satisfied the following constraints: consistent abundances from lines of neutral and ionized Fe and Ti; reasonable predictions for colour-magnitude diagram positions from the derived gravities; no obvious trends of neutral Fe line abundances with EWs; and no obvious trends of neutral Fe line abundances with corresponding excitation potentials. Finally, there is no astrophysical reason for Fe-peak abundances to vary significantly from star to star along the M4 giant branch; V, Ti, Fe, and Ni showed no significant drifts along the RGB.

We present the abundance analyses in the "boxplot" shown in figure 2. The boxplot illustrates the median, data spread, skew and distribution of the range of values we derived for each of the elements from our program stars, along with possible outliers. We determined a metallicity of $\langle \text{[Fe/H]} \rangle = -1.18$ ($\sigma = 0.02$) and found a large abundance ratio range for proton-capture elements such as oxygen, sodium and aluminum. However, the star-to-star variations are small for the heavier elements. Our M4 abundances generally agree well with those of past M4 investigators. The abundances of Ca, Sc, Ti, V, and Ni are also in accord with those of M5 and the halo field. However, the M4 abundances of Ba and La are both overabundant with respect to comparison samples. Yet, the overabundance of Ba in M4 stars has been observed in independent studies by both Brown & Wallerstein (1992) as well as by Lambert *et al* (1992). We also derived high silicon and aluminum abundances, in agreement with previous studies of M4 but significantly higher than the abundances found in either M5 or the field. We explore these issues in the following sub-sections.

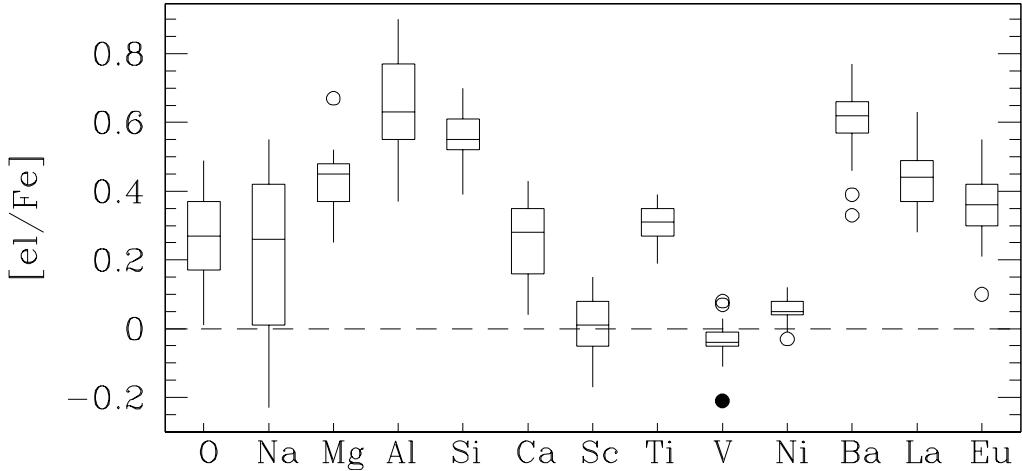


Figure 2: A “boxplot” of the M4 giant star element abundances. For each element, a boxed horizontal line indicates the median value and the interquartile range (the middle 50% of the data). The vertical tails extending from the boxes indicate the total range of abundances determined for each element, excluding outliers. Mild outliers (those between $1.5 \times$ and $3 \times$ the interquartile range) are denoted by hollow circles (o) and severe outliers (those greater than $3 \times$ the interquartile range) by filled circles (●). The dashed line at $[\text{el}/\text{Fe}]$ represents the solar value for a particular elemental abundance ratio (taken from Fig. 7 in Ivans *et al* 1999).

3.1 Proton-Capture Nucleosynthesis

Although several M4 giants exhibit oxygen deficiencies, most M4 giants show little evidence for the severe oxygen depletions observed in M13 (Kraft *et al* 1997) and M15 (Sneden *et al* 1997). Low oxygen abundances are accompanied by low carbon and elevated nitrogen. In addition, the sum of C+N+O is essentially constant, as expected if all stars draw on the same primordial material. We find that the behaviour of O is anti-correlated with that of Na, and, to a lesser degree, with that of Al. These findings are compatible with a proton-capture scenario in which Na and Al are enhanced at the expense of Ne and Mg, respectively (Langer *et al* 1997, Cavallo *et al* 1998). And, we find that the CN-strong stars are those that are more highly processed via proton-capture nucleosynthesis: the CN-strong group has a mean Na abundance that is a factor of two larger than the CN-weak group, and our CN-strong group also has higher Al abundances but the CN-strong/CN-weak difference is much less pronounced. As shown by Langer & Hoffman (1995), very modest hydrogen depletion of the envelope material can lead to an enhancement of Al by +0.4 dex when Na is enhanced by +0.7 dex, exactly as observed in our M4 sample. In this picture, unlike that found in M13 (Shetrone 1996), the enhancement of Al comes about entirely by destruction of ^{25}Mg and ^{26}Mg : ^{24}Mg remains untouched. We attempted to derive the Mg isotope ratios in our spectra and, while there is a hint that the isotopic ratios may not be the same as those found in halo field stars, much higher resolution data is required before one can make statements regarding any differences with certainty.

3.2 α -element Enhancements

Both the magnesium abundances and silicon abundances in M4 exceed those in M5 by a factor of two. However, Ca and Ti abundances in the two clusters are essentially the same and have the usual modest overabundances with respect to the scaled solar ratio. The α - element ratios in M4 mimic those found in the very metal-poor cluster M15. M15, like M4, also exhibits a

high aluminum abundance (that is, a high “floor” of aluminum, on top of which is the proton-capture nucleosynthetic contribution described in the previous subsection). Substructure in α - and light odd elements are also found among relatively metal-rich disk dwarfs (eg. Edvardsson *et al* 1993) and galactic nuclear bulge giants (McWilliam & Rich 1994). While the abundance pairings and trends are not matched between the cluster and disk/bulge populations, it is clear that the differences must arise from some property of the primordial nucleosynthetic sites.

3.3 The Abundances of Ba, La, Eu and ω Cen

The [Ba/Eu] ratio is often used as a measure of *s*- to *r*-process nucleosynthesis in the primordial material of a cluster. Typically, clusters show $-0.6 < [\text{Ba/Eu}] < -0.2$. In M4, [Ba/Eu] is 0.25 dex higher than the total solar-system *r* + *s* and more than four times higher than that of the “normal” cluster M5. However, the high [Ba/Eu] in M4 is not because Eu is low (as is the case in very metal-poor M15), rather, the [Eu/Fe] we find for M4 is not very different from that of M5. The high [Ba/Eu] is due to a high [Ba/Fe]. And, the high abundance of Ba is supported by a high abundance of La. We performed numerical experiments by combining the results of our derived Ba, La, and Eu abundances and found that M4 has a larger *s*:*r*-process contribution than in the sun; the Ba abundance in M4 cannot be attributed to the *r*-process. We find no dependence of the Ba or La abundance on evolutionary state in M4 \Rightarrow these excesses cannot result from neutron captures on Fe-peak elements during a He shell flash episode on the AGB of the stars we observed. It *must* be a signature of *s*-process enrichment of the primordial material out of which the low-mass M4 stars we observed were formed. This excess of the *s*-process elements is evidence that the period of star formation and mass-loss that preceded the formation of the observed stars in M4 was long enough for stars of 3–10 solar masses to evolve into AGB stars and contribute their ejecta into the ISM of the cluster. *s*-process contributions such as those we found in M4 are very well evidenced in the globular cluster ω Cen (Vanture *et al* 1994). Interestingly enough, there exists in ω Cen a subset of stars which possess nearly identical overabundance characteristics in [Ba/Fe], [Al/Fe], [Si/Fe], and [La/Fe] as those found in our M4 stars. However, the multi-metallicity cluster ω Cen also possesses a more complicated nucleosynthetic history than M4. The important point here is that the high Ba and La properties of M4 stars is surely a primordial, not an evolutionary, effect.

4 Conclusions and Future Work

Evidence for proton-capture nucleosynthesis in M4 was expected, and was found to be in good agreement with both observations and theory. However, the overabundances of Ba, La, Si, and Al were not expected and these are still a puzzle. While there are similarities in metallicity, and evolutionary age as observed in the colour-magnitude diagrams of M4 and M5, what nucleosynthetic histories can explain such large differences in the elemental abundances? The Mg isotope ratio in M4 may also be found to be different from that of the field stars, yet another difference that the environment may have imposed on the nucleosynthetic history. Many of the colloquium talks have emphasized the need to attack both more outer halo clusters as well as the disk clusters and do analyses similar to those that have been done for the closest halo clusters. With the successful application of the line-ratio techniques, more detailed abundance analyses will be *able* to be done.

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